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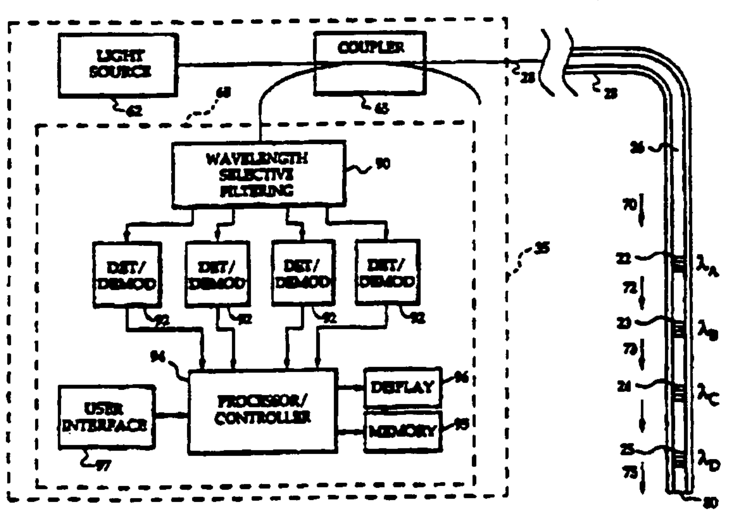
(54) Abstract Title
Fiber optic bragg grating sensor system for use in vertical seismic profiling

(57) A system for vertical seismic profiling of an earth borehole includes an optical fiber (28) having a plurality of Bragg grating sensors (22-25) formed therein, each one of the Bragg grating sensors (22-25) being tuned to reflect a respective bandwidth of light, each bandwidth having a different respective central wavelength. Each of the Bragg grating sensors (22-25) are responsive to an input light signal, a static strain, a dynamic strain and a temperature strain for each providing a respective light signal indicative of static and dynamic forces and temperature at a respective sensor location. The physical spacing and wavelength spacing of the Bragg grating sensors (22-25) are known such that each of the sensing light signals are easily correlated to a specific depth. The Bragg grating sensors (22-25) are tuned such that when a sensor is subjected to a maximum static strain, maximum dynamic strain, and a maximum temperature strain, the maximum wavelength shift of a respective sensing light signal does not cause the frequency of the sensing light signal to enter the bandwidth of another one of the plurality of Bragg grating sensors (22-25).



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(54) Title of Invention

Fiber optic bragg grating sensor system for use in vertical seismic profiling

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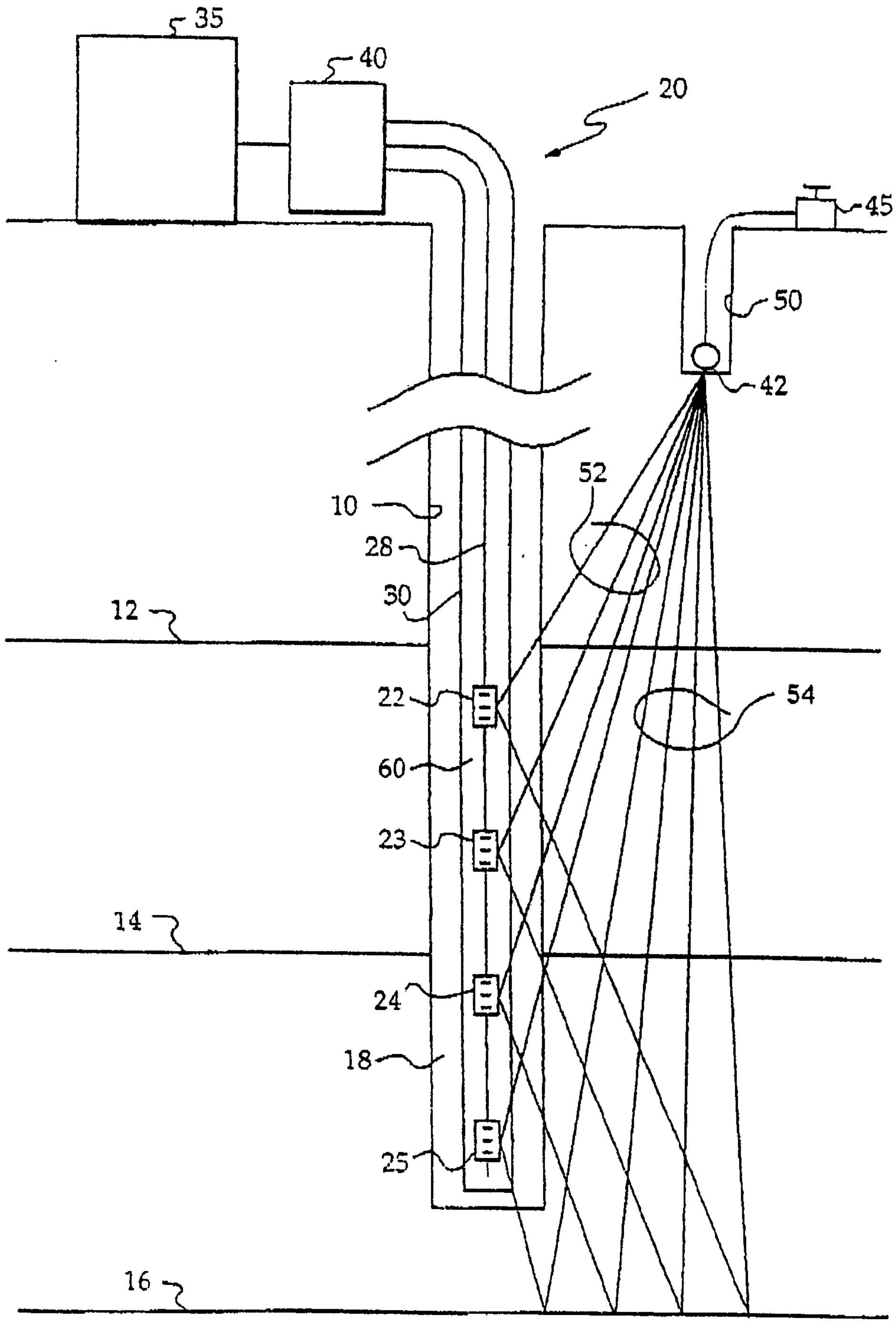
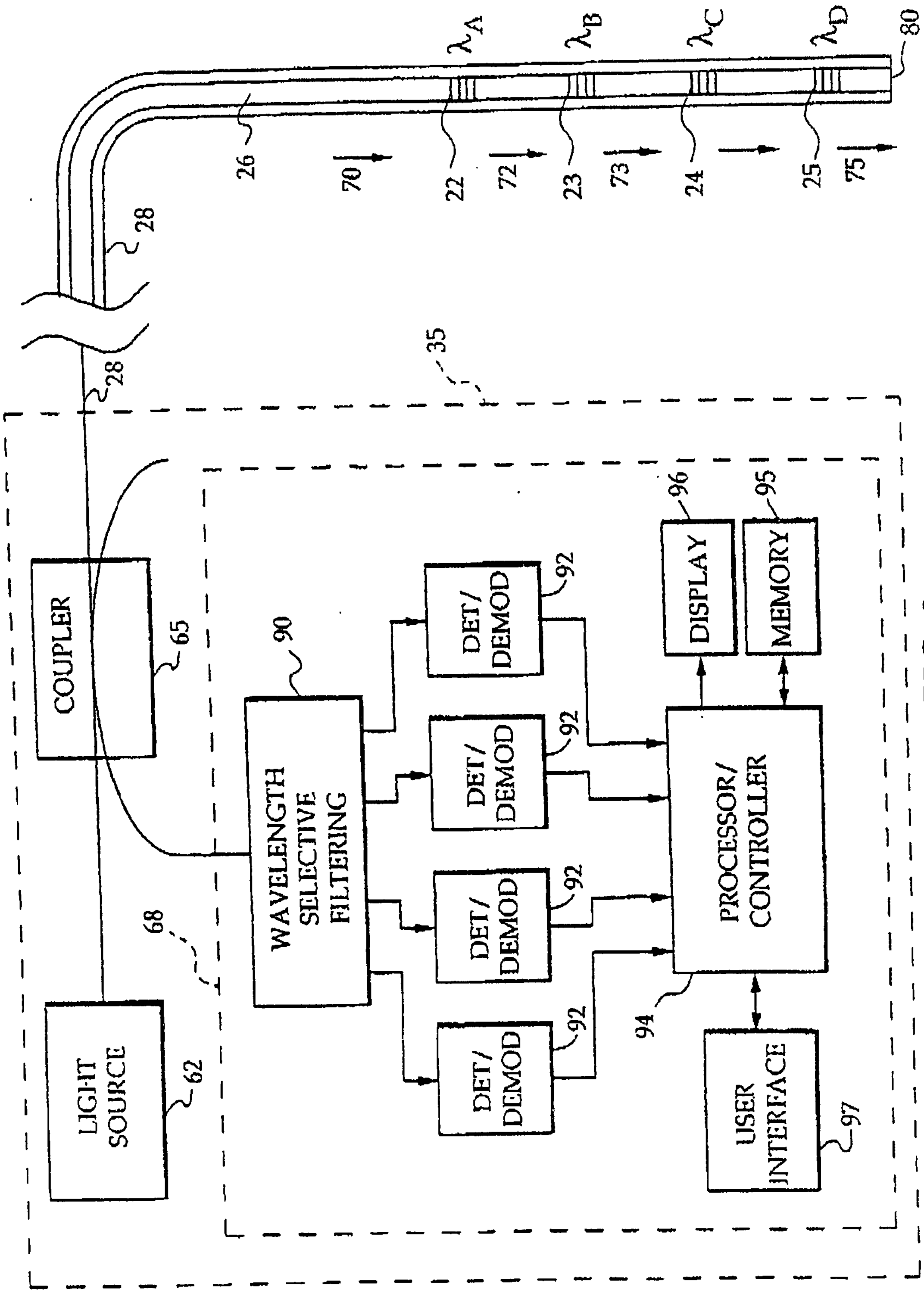


FIG. 1



λA
λB
λC
λD
80
26
70
22
72
23
73
24
25
75
28
28
35
COUPLER
65
LIGHT SOURCE
62
68
WAVELENGTH SELECTIVE FILTERING
90
DET/ DEMOD
92
PROCESSOR/ CONTROLLER
94
DISPLAY
96
MEMORY
95
USER INTERFACE
97

FIG. 2

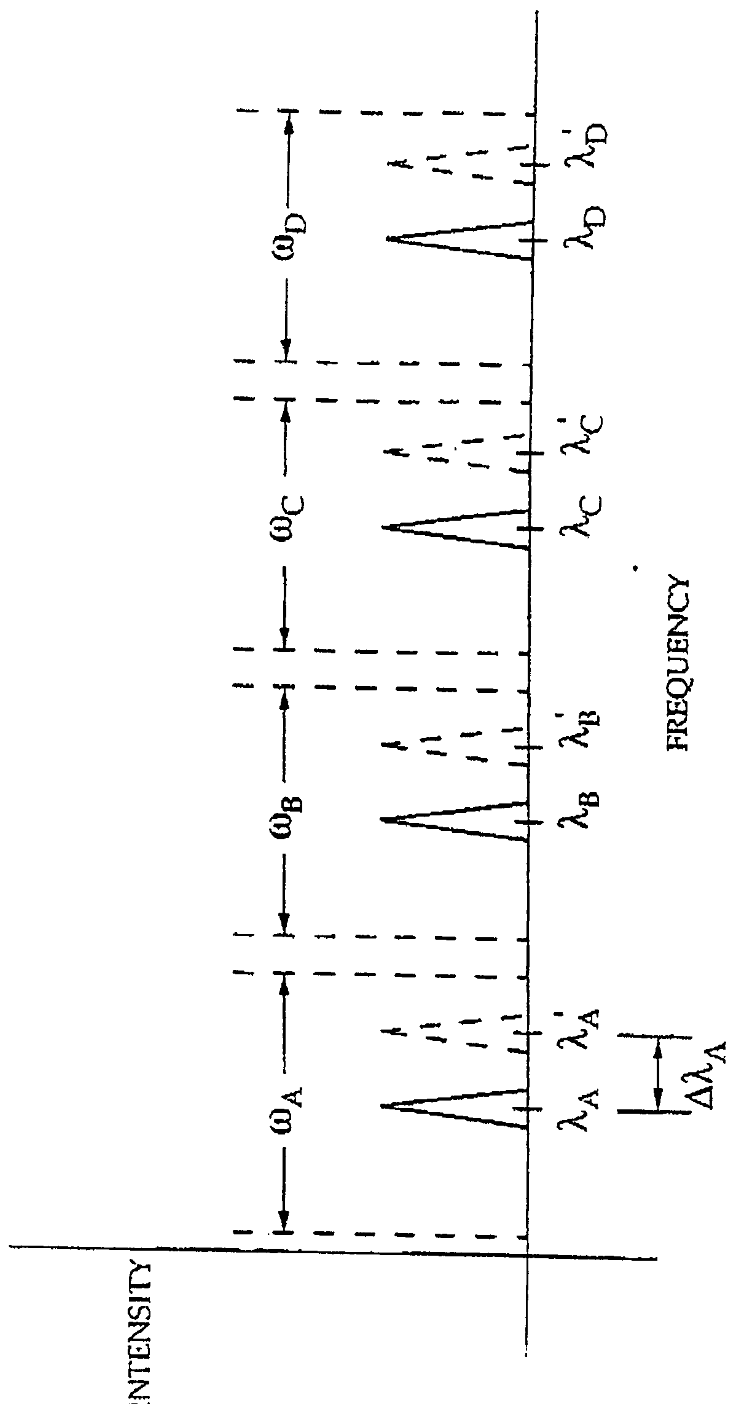

INTENSITY
FREQUENCY
ω_A
ω_B
ω_C
ω_D
λ_A
λ_A'
$\Delta\lambda_A$
λ_B
λ_B'
λ_C
λ_C'
λ_D
λ_D'

FIG. 3

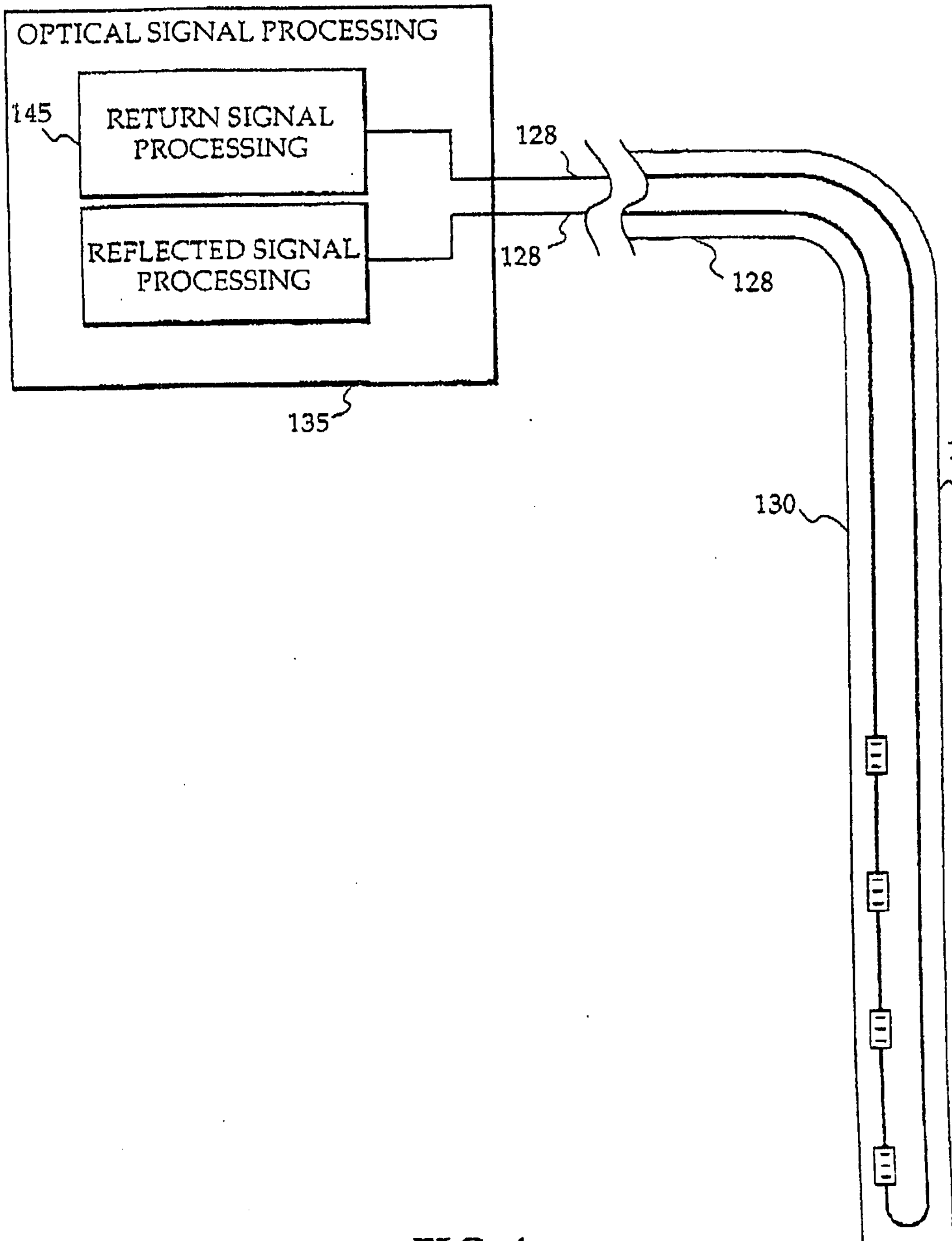

OPTICAL SIGNAL PROCESSING
145
RETURN SIGNAL PROCESSING
REFLECTED SIGNAL PROCESSING
128
128
128
135
140
130

FIG. 4

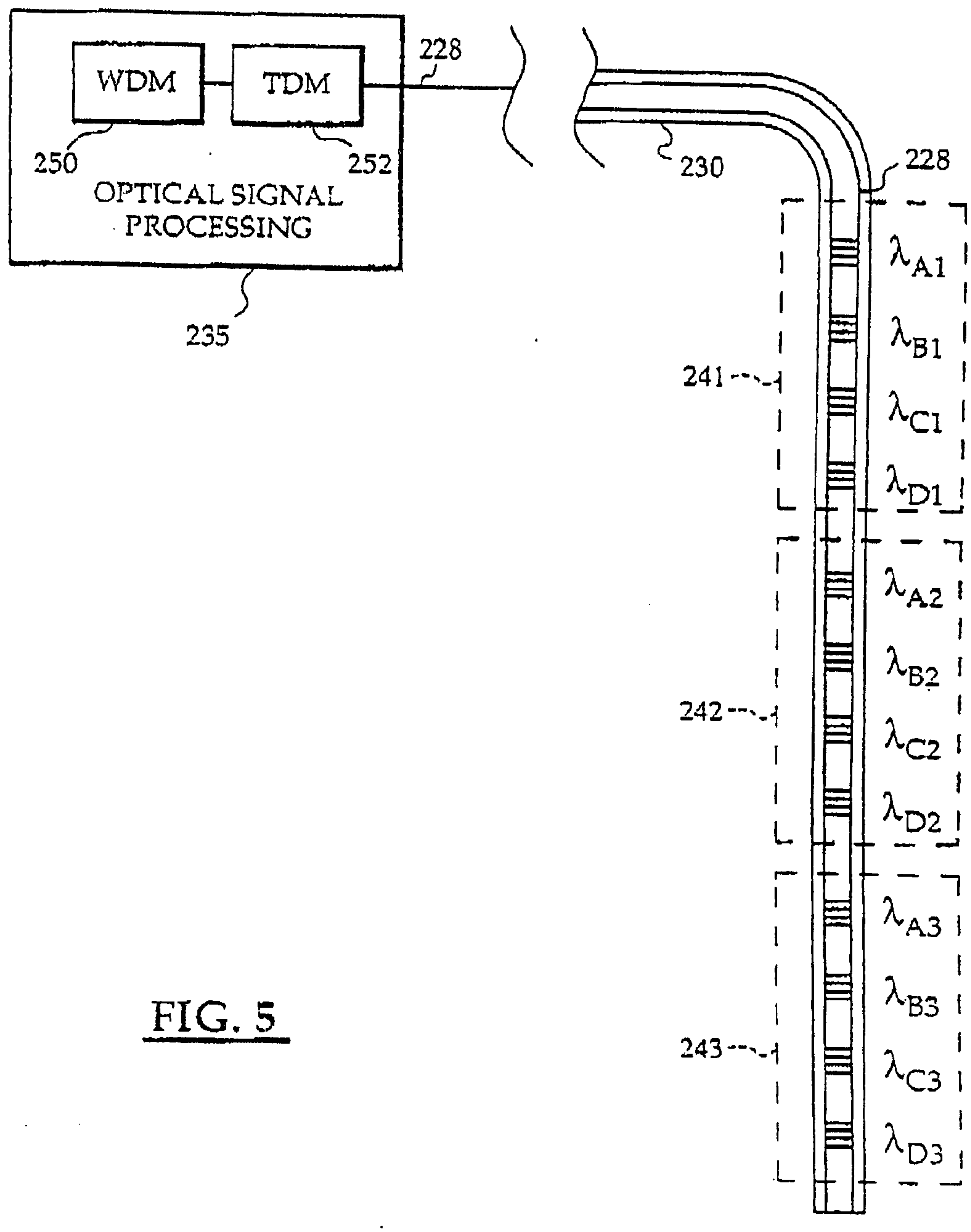

WDM
TDM
228
250
252
OPTICAL SIGNAL PROCESSING
235
230
228
λ_{A1}
λ_{B1}
λ_{C1}
λ_{D1}
241
λ_{A2}
λ_{B2}
λ_{C2}
λ_{D2}
242
λ_{A3}
λ_{B3}
λ_{C3}
λ_{D3}
243

FIG. 5

FIBER OPTIC BRAGG GRATING SENSOR SYSTEM FOR USE IN VERTICAL SEISMIC PROFILING

TECHNICAL FIELD

The present invention relates to fiber optic sensing, and more particularly, to a fiber optic Bragg grating sensor system for use in vertical seismic profiling.

BACKGROUND OF THE INVENTION

Vertical seismic profiling (VSP) is a method of determining acoustic wave characteristics of rock layers in situ. The method includes lowering one or more sensors into a wellbore to a preselected depth. Typically several sensors are spaced apart to allow coverage over a preselected depth interval. A seismic signal is generated at or near the surface of the earth and propagates through the earth to be received by the sensors. These sensors convert the acoustic energy to sensing signals which are transmitted to the surface for suitable processing and recording.

U.S. Patent No. 4,589,285 to Savit issued on May 20, 1996 discloses a vertical seismic profiling arrangement using optical fiber sensors. In particular, the disclosed system includes an elongated cable having a bi-directional optical fiber transmission link therein. A plurality of acousto-optic seismic sensors, each consisting of one- or multi-turn optical fiber coils, are coupled to the optical fiber transmission length by means of suitable directional optical couplers. The optical fiber coil making up each sensor acts as a resonant optical cavity to certain discrete wavelengths, as a function of the local static pressure environment within the borehole fluid. The resonant discrete wavelength under static conditions is the center or reference wavelength. Under dynamic conditions, the reference wavelength is data modulated (wavelength shifted) by transient pressure variations due to acoustic or seismic signals.

In the system disclosed in U.S. Patent No. 4,589,285, each of the sensors are tuned to the same wavelength at the surface, and the varying static pressure, based upon the depth of a sensor, sets up a multitude of different wavelength carriers, each associated with a particular sensor, upon which acoustic seismic data can be superimposed. These different carrier wavelengths caused by the varying static pressure are intended to allow multiple sensors to exist on a single string without interfering with one another.

A problem associated with the VSP method disclosed in U.S. Patent No. 4,589,285 is that the wavelength of any given sensor under static pressure conditions is unknown, and correlation of sensor signals to physical sensors, and therefore sensor depth, is difficult. Further, if the static pressure between two sensors is small, it may be difficult or impossible to differentiate between the signals arising from the individual sensors. Additionally, commercially available techniques for de-multiplexing of wavelength division multiplex signals depend upon knowing the individual signal wavelengths and the channel spacing of the signals being received. Therefore, when using the disclosed method, it is difficult or impossible to guarantee either the absolute wavelengths or spacings of the signals generated by the sensors. The sensors are exposed to the wellbore environment in order to obtain the wavelength shifts associated with the static pressure variation of the fluid column within the wellbore. However, the hostile high temperature and pressure and corrosive environment of an oil or gas wellbore may adversely affect the sensor string.

It is also known to perform distributed sensing utilizing optical Bragg grating sensors which are intrinsic to an optical fiber, see, e.g., U.S. Patent Nos. 4,950,883; 4,996,419; 5,361,130; 5,401,956; 5,426,297; and 5,493,390. In such systems, Bragg gratings are utilized to form Bragg grating sensor strings, where each Bragg grating sensor produces a return signal having an optical bandwidth about a central wavelength (Bragg wavelength). The sensor string may be analyzed on a time

division multiplex basis wherein return signals from various Bragg gratings in the sensor string are uniquely identified by their position in a pulse train of signals, such as disclosed in U.S. Patent No. 5,361,130. Alternatively, as disclosed in U.S. Patent No. 5,401,956, each Bragg grating sensor may have a central reflection wavelength different from that of the other fiber Bragg gratings such that the signals reflected by the Bragg grating sensor string are uniquely identified based on the wavelength of the received signals in a wavelength division multiplex system.

While such distributed fiber Bragg grating sensor systems have been utilized for distributed sensing of strain, temperature or other perturbations, such sensor systems have not been utilized for vertical seismic profiling in an earth borehole. In particular, as described above, an earth borehole of an oil or gas well presents an extremely hostile environment because of the high temperature, pressure and corrosive environment.

There therefore exists a need for an improved system for vertical seismic profiling of an earth borehole which provides highly accurate and reliable indication of seismic conditions while at the same time being resistant to the extremely hostile environment of an earth borehole.

According to the present invention there is provided a vertical seismic profiling system for performing a vertical seismic profile of an earth formation in relation to a borehole, comprising:

a device for producing a seismic disturbance force arranged at a selected distance from the borehole;

an optical fiber in which Bragg grating optical seismic sensors are formed distributed along a selected length of the borehole, said sensors being spaced at desired intervals along the optical fiber in the borehole,

each of said sensors being responsive to an optical signal transmitted along the optical fiber and to the disturbance force thereat to generate in said optical fiber an optical seismic sensor signal; and

optical signal processing equipment coupled to said optical fiber to provide said optical signal thereto and responsive to the optical seismic sensor signals to provide vertical seismic profile information about the earth formation.

There will be described hereinafter a system embodying the present invention which is suitable for vertical seismic profiling over a long depth within an earth borehole and which provides accurate and reliable seismic profiling information which is easily correlated to specific depths.

There will be further described such a system which is resistant to damage caused by the high temperature, pressure and corrosive hostile environment of an earth borehole.

In the described embodiment of a system for vertical seismic profiling of an earth borehole, which includes an optical fiber having a plurality of Bragg grating sensors formed therein, each one of the Bragg grating sensors is tuned to reflect a respective bandwidth of light, each bandwidth having a different respective central wavelength. The plurality of Bragg grating sensors are each responsive to an input light signal, a static strain, a dynamic strain and a temperature strain, each providing a respective light signal indicative of static and dynamic forces and temperature at a respective sensor location.

Moreover, the physical spacing and wavelength spacing of the Bragg grating sensors are known such that each of the sensing light signals are easily correlated to a specific depth. The Bragg grating sensors are tuned such that when a sensor is subjected to a maximum static strain, maximum dynamic strain, and a maximum temperature strain, the maximum wavelength shift of a respective sensing light signal does not cause the frequency of the sensing light signal to enter the bandwidth of another one of the plurality of Bragg grating sensors.

In summary the system embodying the invention disclosed below provides sensing light signals associated with particular sensors which are easily differentiated from one another so that a highly accurate and reliable indication of the vertical seismic profile is provided. Each of the signals is easily differentiated from one another, and is easily associated with a specific depth of a sensor. Additionally, the sensor string is provided with a sensor string delivery system which protects the sensor string from the hostile environment of an earth borehole, such as an oil or gas well, while at the same time providing a reliable and accurate indication of the seismic signals of interest

In one development of the system, the seismic sensors are arranged in a plurality of sets, the sets being located at different distances along the optical fiber. Provision is made for using wavelength division multiplex to differentiate the signals generated within a set and time division multiplex to differentiate the signals generated from different sets.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a cross-sectional view of an earth borehole having a Bragg grating sensor string of the invention deployed therein for vertical seismic profiling;

Fig. 2 is a more detailed schematic block diagram of the Bragg grating sensor string of Fig. 1;

Fig. 3 is a graph showing the reflectivity profile of four Bragg grating sensors;

Fig. 4 is a schematic block diagram of a second embodiment of the Bragg grating sensor string of Fig. 1; and

Fig. 5 is a schematic block diagram of a third embodiment of the Bragg grating sensor string of Fig. 1.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring to Fig. 1, a borehole **10**, such as an oil or gas well, penetrates various earth layers **12, 14, 16**. Such a borehole may be fifteen to twenty thousand feet or more in depth. As is known in the art, the borehole is filled with a high temperature and pressure drilling fluid **18** which presents an extremely corrosive and hostile environment.

An optical fiber sensor string **20** includes Bragg grating sensor elements **22, 23, 24, 25** formed within a core **26** (Fig. 2) of an optical fiber **28**. The optical fiber **28** is positioned within a capillary tube **30**.

Bragg gratings (fiber gratings) are well suited for use as sensor elements. When a fiber grating is illuminated, it reflects a narrow band of light at a specified wavelength. However, a measurand, such as strain induced by dynamic or static pressure or temperature, will induce a change in the fiber grating spacing and/or reflectivity characteristics, which changes the wavelength of the light it reflects. The value (magnitude) of the measurand is directly related to the wavelength reflected by the fiber grating and can be determined by detecting the wavelength or phase shift characteristics of the reflected light.

The optical fiber sensor string 20 is interconnected to optical signal processing equipment 35 via well-known capillary tube delivery equipment 40 for delivering the optical fiber 28 within the capillary tube 30 down the borehole 10. The tubing delivery equipment 40 provides for the delivery of the capillary tubing 30 and optical fiber 28 down the borehole 10, while providing for the delivery of optical signals between the optical signal processing equipment 35 and the optical fiber 28, either directly or via interface equipment (not shown) as required.

For performing the vertical seismic profiling, the optical fiber sensors are distributed over a known length, such as 1,524 m (5,000 feet). Over the known length, the Bragg grating sensors 22, 23, 24, 25 are evenly spaced at a desired interval, such as every 3-6 m (10 to 20 feet), for providing the desired vertical seismic profiling. As described in greater detail herein, each sensor reflects a narrow wavelength band of light having a central wavelength. Each sensor operates at a different wavelength band and central wavelength such that the signals may be easily detected using Wavelength Division Multiplexing (WDM) techniques. The entire optical fiber, positioned within the capillary tube 30, is lowered to a desired depth, for example as measured from the upper most sensor, such as 305 m (1,000) feet). An acoustic wave source, such as a small charge of dynamite 42 (a seismic shot), is detonated by a blaster 45 in a shallow shothole 50 that is offset from the borehole 10 by a selected distance, such

as 914 m (3,000 feet).

In an alternative embodiment of the invention, the fiber may be provided to extend the entire length of the well, e.g., 4,572 to 6096 m (15,000 to 20,000 feet), with the Bragg grating sensors **22, 23, 24, 25** evenly spaced at desired intervals along the length of the fiber. The sensors may be provided as a single WDM set as illustrated in Figs. 1 and 2. Alternatively, as illustrated in Fig. 5, a plurality of WDM sets **241, 242, 243** may be combined by Time Division Multiplexing (TDM) sets of the WDM sets. For example, for a 6,096 m (20,000 foot) well, 400 sensor points are required for a sensor spacing of 15.25 m (50 feet). This may be achieved for example by a single WDM set of sensors. Alternatively, four sets of sensors each containing 128 WDM sensors may be TDM together for a total of 512 sensors. In this case, a spacing of less than 12 m (40 feet) between sensors can be used.

Returning to Fig. 2, acoustic waves radiate from the shot along a direct path **52** and a reflected path **54**. The reflected waves **54** are reflected off of the various earth layers **12, 14, 16**. As will be described in greater detail hereinafter, the direct seismic waves **52** and reflected seismic waves **54** are detected by the sensors **22, 23, 24, 25**. Resulting data signals are transmitted through the optical fiber **28** to the optical signal processing equipment **35**. In one embodiment of the invention, after the seismic shot, the optical sensor string **20** is repositioned within the borehole for additional seismic profiling. In a second embodiment of the invention, the Bragg grating sensors **22, 23, 24, 25** are distributed over the entire length of the optical fiber **28** such that the entire borehole **10** is characterized in a single shot. In order to improve the transmission of acoustic signals through the capillary tube **30** to the Bragg grating sensors **22, 23, 24, 25** the capillary tube **30** may be filled with a high-density low-compressibility material 60, such as the material disclosed in U.S. Patent 5,767,411, the disclosure of which is incorporated herein by reference.

Referring now to Fig. 2, the optical signal processing equipment 35 includes a broadband source of light 62, such as an edge emitting light emitting diode (ELED) or laser, and appropriate equipment for delivery of signal light, such as a coupler 65, to the optical fiber 28 for transmission to the Bragg grating sensors 22, 23, 24, 25 included within the core 26 of the optical fiber 28. Additionally, the optical signal processing equipment 35 includes appropriate signal analysis equipment 68 for analyzing the return signals from the Bragg gratings 22, 23, 24, 25. The broadband light source signal 70 passes through the core 26 of the optical fiber until it reaches the first Bragg grating sensor 22. A Bragg grating sensor, as is known, is a periodic refractive index variation in the core of an optical fiber that reflects a narrow wavelength band of light, has a maximum reflectivity at a central reflectivity wavelength, and transmits all other wavelengths. Thus, when the broadband light source signal 70 is incident on the first Bragg grating sensor 22, a narrow wavelength band of light having a central wavelength λ_A is reflected therefrom, and light not reflected is transmitted through the grating 22 as indicated by light 72. The light 72 is incident on a second Bragg grating sensor 23, having a narrow wavelength band of light with a central reflectivity wavelength λ_B. Light 73 not reflected by the second Bragg grating sensor 23 is transmitted to the third Bragg grating sensor 24. The grating 24 reflects a narrow wavelength band of light having a central reflective wavelength of λ_C. Light 74 not reflected by the third grating 24 is transmitted to the fourth Bragg grating sensor 25. Again, this Bragg grating sensor 25 reflects a narrow wavelength band of light having a central wavelength λ_D. The remaining light 75 not reflected by the fourth Bragg grating sensor 25 is provided to the end of the optical fiber 80.

The end 80 of the optical fiber 28 is terminated in an anti-reflective manner, so as to prevent interference with the reflected wavelengths from the Bragg grating sensors 22, 23, 24, and 25. For example, the end 80 of the optical fiber 28 may be cleaved at an angle so that the end face is not perpendicular to the fiber axis. Alternatively, the end 80 of the optical fiber 28 may be coated with a material that

matches the index of refraction of the fiber, thus permitting the light 75 to exit the fiber without back reflection, and be subsequently dispersed in the index-matching material.

Referring to Fig. 4, in another embodiment of the invention, rather than terminating the optical fiber in an anti-reflective manner, the optical fiber 128 may be looped back to the surface within the tube 130. The portion of the fiber 140 returning to the surface may or may not have gratings in it. This return fiber portion 140 may be used to check for fiber integrity by monitoring the entire loop at the optical signal processing equipment 135 to ensure that there are no breaks or degradation of the fiber. Changes in the light not reflected by any of the Bragg gratings and returned to the surface by the return fiber portion 140 may be monitored 145 to detect problems with the fiber. Therefore, variations in the sensor return signals caused by problems with the fiber are easily differentiated from changes in the return signals associated with strain caused by temperature and static and dynamic pressure.

Referring also to Figs. 1 and 3, the fiber Bragg gratings 22, 23, 24, 25 will experience strain due to several environmental factors including temperature, static pressure associated with the column of noncompressible fluid 60 within the capillary tube 30, and acoustic pressure associated with the seismic waves 52, 54. As discussed above, these strains will cause a wavelength shift in the central wavelength of the narrow band of light reflected by each Bragg grating sensor. For example, when the first Bragg grating sensor 22 is subjected to the static strain (from the static pressure of the noncompressible fluid) the dynamic strain (from the seismic waves) and the temperature strain, the central wavelength λ_A shifts by an amount $\Delta\lambda_A$ to a new central wavelength λ_A'. Each of the Bragg grating sensors 22, 23, 24, 25 are designed to provide a wavelength spacing such that when the central wavelength of one of the Bragg grating sensors shifts by a maximum amount associated with a maximum dynamic, static and temperature strain, the central wavelength will still be in a desired bandwidth ω which does not overlap with any of the other Bragg grating sensors.

Therefore, as illustrated in Fig. 3, with respect to the first Bragg grating sensor **22**, the shifted central wavelength λ_A' will always be within a selected bandwidth ω_A for the Bragg grating sensor **22** which does not overlap with the selected bandwidth ω_B, ω_C, ω_D of the other Bragg grating sensors **23**, **24**, **25**, respectively.

Referring again to Fig. 2, the reflected optical signals λ_A', λ_B', λ_C' and λ_D' are provided via the optical fiber **28** and the coupler **65** to the signal analysis equipment **68**. In one embodiment of the invention, the signal analysis equipment **68** is only concerned with the dynamic strain associated with the seismic waves, and therefore, compensation for temperature variation and static pressure is not provided. The seismic measurements are only taken after the sensor string is in place within the borehole and reaches equilibrium temperature and static pressure conditions. Thereafter, any variation in the central wavelength associated with the Bragg grating sensors will be primarily due to the dynamic strain caused by the seismic signals.

In order to separate the responses from the different gratings **22**, **23**, **24**, **25**, the return optical signals are directed to a wavelength selective filter or router **90**. This device **90** separates the optical signals produced by each Bragg grating by means of selective filtering. The passbands of this device correspond to the selected bandwidths ω_A, ω_B, ω_C and ω_D of each of the Bragg grating sensors **22**, **23**, **24**, **25**, respectively, to ensure that the optical signals produced by the individual Bragg grating sensors are always passed. In one embodiment of the invention, the wavelength selective filter **90** provides a separate output associated with each sensor to be analyzed using sensitive wavelength or phase discrimination equipment **92** which detects, demodulates and performs wavelength or phase discrimination to determine the wavelength modulation effects due to the seismic waves. Alternatively, a single wavelength or phase discriminator may be provided, and the wavelength selective filtering may be designed to store and forward the frequency response of the individual Bragg gratings such that the wavelength modulation may be determined individually for each Bragg grating sensor.

The output of the sensitive wavelength or phase discrimination equipment 92 is provided to a processor/controller 94 for processing, storage in memory 95, display 96 to a user, or for any other desired use. The processor 94 may be provided with a user interface 97 for user input and control, for example to generate reports illustrating the results of the vertical seismic profiling.

As will be understood by those skilled in the art, the wavelength selective filtering includes wavelength division demultiplexer which is used to separate the wavelength components onto separate fibers which are then each analyzed via separate high resolution wavelength discriminators. An example of the type of wavelength discrimination suitable for this purpose is the interferometric detection approach described in U.S. Patent No. 5,361,130, the disclosure of which is incorporated herein by reference.

Although a specific embodiment of the optical signal processing equipment is described above, other optical signal analysis techniques may be used with the present invention such as the necessary hardware and software to implement the optical signal diagnostic equipment disclosed in U.S. Patent Nos. 4,996,419; 5,401,956; 5,426,297; and/or 5,493,390, the disclosures of which are incorporated herein by reference.

As is well known in the art, there are various optical signal analysis approaches which may be utilized to analyze return signals from Bragg gratings. These approaches may be generally classified in the following four categories:

1. Direct spectroscopy utilizing conventional dispersive elements such as line gratings, prisms, etc., and a linear array of photo detector elements or a CCD array;

2. Passive optical filtering using both optics or a fiber device with wavelength-dependent transfer function, such as a WDM coupler;

3. Tracking using a tuneable filter such as, for example, a scanning Fabry-

Perot filter, an acousto-optic filter such as the filter described in the above referenced U.S. Patent No. 5,493,390, or fiber Bragg grating based filters; and

4. Interferometric detection.

The particular technique utilized will vary, and will depend on the Bragg wavelength shift magnitude (which depends on the sensor design) and the frequency range of the measurand to be detected.

As will be further understood by those skilled in the art, the optical signal processing equipment may operate on a principle of WDM as described above wherein each Bragg grating sensor is utilized at a different passband or frequency band of interest. Alternatively, as discussed above, the present invention may utilize TDM, either alone or in combination with WDM, for obtaining signals from multiple independent sensors or multiple independent sets of WDM sensors, or any other suitable means for analyzing signals returned from a plurality of Bragg grating sensors formed in a fiber optic sensor string.

The invention has been described with respect to Figs. 1 and 2 as providing a single set or group of Bragg grating sensors, wherein each sensor in the group operates in a unique frequency band such that the signals from the individual sensors may be easily identified using wavelength division multiplexing techniques. However, as briefly described above with respect to Fig. 5, multiple sets of Bragg grating sensors may be combined using time division multiplexing techniques. Referring to Fig. 5, three sets of Bragg grating sensors **241, 242, 243** are essentially identical with respect to the number of sensors, the bandwidths of the sensors and the central wavelengths of the sensors. The difference between the sets of Bragg grating sensors **241, 242, 243** is the positioning of the sets along the length of the optical fiber **228**. Wavelength division multiplexing optical signal processing equipment **250** is used to differentiate between the signals provided by the individual sensors within a set of sensors. However, time division multiplexing optical signal processing

equipment 252 is utilized to differentiate between the signals provided by each set of sensors. This arrangement provides certain advantages. The same optical signal processing equipment 235 may be utilized to analyze the return signal from all of the sets of Bragg grating sensors 241, 242, 243 because the sensor sets utilized the same wavelengths. Therefore, each of the sets requires the same wavelength selective filtering and wavelength or phase discrimination equipment. Time division multiplexing techniques, disclosed for example in U.S. Patent No. 5,364,180, the disclosure of which is incorporated herein by reference, may be utilized to differentiate between the signals from each of the sets.

In addition to the use of a single reflective grating as a Bragg grating sensor 22, 23, 24, 25, (Fig. 2) as explained herein, an alternate embodiment of this invention can utilize a pair of reflective gratings within the same length of fiber, thus forming a resonant cavity of longer length. Such a resonant cavity will also reflect light of a particular wavelength corresponding to a central wavelength of the reflective gratings. A change in the cavity length due to a static strain, a dynamic strain and/or a temperature induced strain on fiber will result in phase shift in the reflected light due to the change in optical path length within the reflective cavity. Such a device, termed a Fabry-Perot interferometer, can then provide a high sensitivity means of detecting strain in the optical fiber, and the resultant optical phase shift can be detected using standard interferometer instrumentation techniques. Thus, it is possible with this technique to realize a Bragg grating sensor which has enhanced sensitivity. Alternatively, the pair of Bragg gratings may be used to form a lasing element for detection, for example by positioning an Erbium doped length of optical fiber between the pair of Bragg gratings.

~~I claim:~~

CLAIMS

1. A vertical seismic profiling system for performing a vertical seismic profile of an earth formation in relation to a borehole, comprising:

a device for producing a seismic disturbance force arranged at a selected distance from the borehole;

an optical fiber in which Bragg grating optical seismic sensors are formed distributed along a selected length of the borehole, said sensors being spaced at desired intervals along the optical fiber in the borehole,

each of said sensors being responsive to an optical signal transmitted along the optical fiber and to the disturbance force thereat to generate in said optical fiber an optical seismic sensor signal; and

optical signal processing equipment coupled to said optical fiber to provide said optical signal thereto and responsive to the optical seismic sensor signals to provide vertical seismic profile information about the earth formation.

2. A profiling system as claimed in Claim 1 in which each of said sensors is tuned to a different central wavelength in respect of the bandwidth of light reflected thereby in response to said optical signal.

3. A profiling system as claimed in Claim 2 in which each sensor is tuned such that the maximum wavelength shift of its central wavelength associated with a maximum dynamic, static and temperature strain does not overlap into the bandwidth of any other sensor.

4. A profiling system as claimed in Claim 1, 2 or 3 in which said optical fiber and the sensors distributed therealong is positioned in the borehole within a capillary tube.

5. A profiling system as claimed in Claim 4 in which the capillary tube is filed with a high-density, low-compressibility material to enhance transmission of acoustic signals through the capillary tube to the sensors.

6. A profiling system as claimed in any one of Claims 1 – 5 in which said optical fiber is terminated in a light-absorbent load at its lower end.

7. A profiling system as claimed in any one of Claims 1 – 5 in which said optical fiber extends beyond the lowermost sensor in the borehole in a return path to said optical signal processing equipment.

8. A profiling system as claimed in any preceding Claim in which said optical signal processing equipment comprises a light source for providing said optical signal to the optical fiber, signal analysis equipment responsive to said sensor signals to provide the vertical seismic profile information of the earth formation, and a coupler coupling said light source to said optical fiber to provide said optical signal thereto and coupling said optical fiber to said signal analysis equipment to transmit said sensor signals thereto.

9. A profiling system as claimed in Claim 8, wherein

the signal analysis equipment comprises at least one wavelength selective filter or router, wavelength or phase discrimination equipment, and a processor/controller;

the at least one wavelength selective filter or router separates the sensor signals from respective Bragg grating sensors using selective filtering;

the wavelength or phase discrimination equipment responds to the separated sensor signals, and demodulates and performs wavelength or phase discrimination thereon; and

the processor/controller processes the respective demodulated and discriminated sensor signals to provide the vertical seismic profile information of the earth formation.

10. A profiling system as claimed in Claim 9, wherein

the signal analysis equipment further comprises a memory for storing signals, a display for providing visual information to a user, and a user interface for allowing user interaction with the vertical seismic profiling system.

11. A profiling system as claimed in any preceding Claim, wherein

the direct mechanical-to-optical energy conversion of each Bragg grating optical seismic sensor converts a wavelength or a phase of said optical signal to generate its respective optical seismic sensor signal.

12. A profiling system as claimed in claim 4 or 5 further comprising tube delivery equipment for delivering said optical fiber and the sensors distributed therealong with the capillary tube down the borehole.

13. A profiling system as claimed in Claim 7, wherein

the optical signal processing equipment includes a return signal processing means and a reflected signal processing means.

14. A profiling system as claimed in Claim 1 in which said seismic sensors are arranged in a plurality of sets, the sets being located at different distances along the optical fiber, and

said optical signal processing equipment including wavelength division multiplex means to differentiate the sensor signals generated within a set and time division multiplexing means to differentiate the sensor signals generated from different sets.

15. A profiling system as claimed in Claim 14 in which within each set the sensors in that set are tuned to a different central wavelength in respect of the bandwidth of light reflected thereby in response to said optical signal.

16. A profiling system as claimed in Claim 15 in which within each set each sensor is turned such that the maximum wavelength shift of its central wavelength associated with a maximum dynamic, static and temperature strain does not overlap into the bandwidth of any other sensor of that set.

17. A profiling system as claimed in any preceding Claim, wherein

the length of the optical fiber along which said sensors are distributed is such that the entire borehole is characterized in a single seismic disturbance force.

18. A profiling system as claimed in any one of Claims 1 – 16, wherein

the length of the optical fiber along which said sensors are distributed is such that less than the entire borehole is characterized in one seismic disturbance force.

19. A profiling system as claimed in any one of Claims 1 – 13 in which said sensors are evenly distributed along said optical fiber for the entire length of the borehole.

20. A profiling system as claimed in any one of Claims 1 – 13 in which said sensors are evenly distributed along said optical fiber for part of the length of the borehole.

21. A profiling system as claimed in any one of Claims 14, 15 and 16, in which in each set the sensors therein are evenly distributed along said optical fiber.

22. A profiling system as claimed in any one of Claims 1 – 5, wherein said sensors have a physical spacing along the optical fiber and a central wavelength spacing of their respective bandwidths that are selected so that each of the sensors provides a respective seismic sensor signal that is correlated to a specific depth in the borehole.

23. A profiling system as claimed in any preceding Claim, wherein

the selected length of the borehole is in a range of 4572 to 6096 metres (15,000 to 20,000 feet);

the selected distance between the seismic disturbance force means and the borehole is about 914 metres (3,000 feet); and

the optical fiber over which the Bragg grating optical seismic sensors are distributed is about 1524 metres (5,000 feet).